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RESEARCH MEMORANDUM

THE EFFECTS OF FUEL SLOSHING ON THE LATERAL STABILITY OF A FREE-FLYING AIRPLANE MODEL

By

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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THE EFFECTS OF FUEL SLOSHING ON THE LATERAL STABILITY OF A FREE-FLYING AIRPLANE MODEL

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SUMMARY

An investigation has been made in the Langley free-flight tunnel to determine the effect of the sloshing of fuel in partly filled, unbaffled tanks on the lateral stability of a free-flying model. Two transparent plexiglass spheres 8 inches in diameter, mounted fore and aft equidistant from the center of gravity, were used to simulate fuel tanks. For convenience, water was used instead of fuel for this investigation. Flight tests were made to determine the effects of the water sloshing for different depths of water and various masses and moments of inertia of the model. Because of the speed limitations of the tunnel the flight tests did not cover the condition where the natural periods of the model and the water were the same.

The sloshing of the water in the tanks caused small-amplitude, high-frequency lateral oscillations which were superimposed on the normal Dutch roll oscillation so that the lateral motions of the model appeared jerky. The effects of the water sloshing were most pronounced when the tanks were between one-seventh and one-third full of water.

INTRODUCTION

Considerable trouble has been experienced recently with snaking or lightly damped Dutch roll oscillations on several high-speed airplane designs. In some cases, it was thought that this trouble might be caused by the sloshing of the fuel which might reinforce the natural oscillations of the airplane for some flight conditions. In the past, the fuel sloshing has been relatively unimportant because the weight of the fuel was generally small compared to the weight of the airplane and even when large quantities of fuel were used it was carried in a number of small tanks. In some recent airplanes, however, provision has been made for such large quantities of fuel that the weight of fuel is approximately equal to the empty weight of the airplane and all of this fuel is carried in one or two large tanks. Under such conditions the sloshing of the fuel might be an important factor in the oscillatory stability of the airplane. An investigation has been made, therefore, in the Langley free-flight tunnel to determine whether the fuel sloshing might be expected to have an appreciable effect on the oscillatory stability of an airplane.

A flying model was equipped with two large spherical tanks in which water was used to simulate fuel. Flight tests were made with this model over a range of test conditions which included various fuel loads, empty weights, and moments of inertia.

SYMBOLS

All forces and moments were referred to the stability axes which are defined in figure 1.

W weight of model, pounds $(W_e + W_f)$

W_e empty weight of model, pounds

W_f weight of fuel (water), pounds

I_x moment of inertia of model about longitudinal body axis of inertia, slug-feet^2

I_y moment of inertia of model about lateral body axis of inertia, slug-feet^2

I_z moment of inertia of model about normal body axis of inertia, slug-feet^2

S wing area, square feet

b wing span, feet

ρ mass density of air, slugs per cubic foot

ϕ angle of bank, degrees

ψ angle of yaw, degrees

β angle of sideslip, degrees

θ angle of pitch, degrees

C_Y lateral-force coefficient $\left(\frac{\text{Lateral force}}{qS}\right)$

C_l rolling-moment coefficient $\left(\frac{\text{Rolling moment}}{qSb}\right)$

C_n yawing-moment coefficient $\left(\frac{\text{Yawing moment}}{qSb}\right)$

C_{l_β} rate of change of rolling-moment coefficient with angle of sideslip in degrees $\left(\frac{\partial C_l}{\partial \beta}\right)$

C_{n_β} rate of change of yawing-moment coefficient with angle of sideslip in degrees $\left(\frac{\partial C_n}{\partial \beta}\right)$

C_{Y_β} rate of change in lateral-force coefficient with angle of sideslip in degrees $\left(\frac{\partial C_Y}{\partial \beta}\right)$

APPARATUS

The investigation was conducted in the Langley free-flight tunnel which is equipped to test free-flying models as described in reference 1.

A three-view sketch and photographs of the model are presented in figures 2 and 3. The mass and dimensional characteristics of the model are given in tables I and II. The model had an unswept wing with an aspect ratio of 6 and a taper ratio of 0.5. A boom-type fuselage was used to support the tail surfaces and the two 8-inch-diameter, transparent, spherical tanks which were mounted fore and aft equidistant from the center of gravity. With this arrangement only the vertical location of the center of gravity varied when equal amounts of water, which was used to simulate fuel, were put in each tank.

Ballasting the model to vary the mass and moments of inertia for the empty condition was accomplished by mounting detachable lead weights to the nose, tail, wing tips, and center of gravity. A weight or combination of weights could easily be removed to alter the mass and moments of inertia, either independently or simultaneously.

TESTS

Flight tests of the model were made at a lift coefficient of 1.0 with the model in four different basic conditions (designated A, B, C, and D) which represented different mass characteristics for the empty condition as shown in table I. For each of these basic conditions the depth of water in the tanks was varied and is indicated by the subscripts following the letter designating the basic condition. These subscripts give the depth of the water in the tanks in inches; that is, condition B_3 indicates basic condition B with 3 inches of water in each of the tanks. The range of the tests is indicated by figure 4 which shows the variation of mass ratio W_f/W for each test condition and for an existing full-scale airplane with geometrically similiar tanks.

Motion-picture records of the flight tests were made with cameras mounted at the top and rear of the tunnel and time histories of the lateral motions of the model were obtained from these records. The movements of the lateral controls were noted when they were recorded on the film. Notes were also made of the pilot's opinion of the relative ease with which the model could be flown for each of the test conditions.

Force tests were made to determine the static lateral stability derivatives of the model. These derivatives were determined from yaw tests at the angle of attack at which the model was flown.

Some tests were also made to determine the natural period and damping of water at various depths in the tanks. For these tests a tank containing water was agitated to start the water sloshing, then the tank was fixed and the ensuing motion of the water was recorded with a motion-picture camera so that the angle of the surface of the water relative to the horizontal could be determined.

RESULTS AND DISCUSSION

The static lateral stability derivatives of the model as measured in the force tests were

$$C_{Y_\beta} = -0.01400$$

$$C_{l_\beta} = -0.00244$$

$$C_{n_\beta} = 0.00297$$

Typical time histories of the lateral motions of the model in the various test conditions are presented in figures 5 to 8 and time histories of the natural motions of the water in the tanks following a disturbance are presented in figure 9. It can be seen from these records that the natural period of the lateral oscillation of the model was of the order of 1.5 seconds whereas the natural period of the water was about 0.55 second. Hence, the flight tests did not cover the condition where the natural periods of the model and the water were the same. This is the condition where the greatest effect of the water sloshing reinforcing the model oscillation could be expected.

The flight records show that, even though the natural periods of the water and the model were not the same, the sloshing of the water caused lightly damped lateral motions in the form of high-frequency, small-amplitude oscillations which were superimposed on the normal motions of the model so that the lateral motions appeared jerky. The period of these high-frequency oscillations was about 0.2 to 0.3 second which is considerably less than the natural period of the water or the model. The motions of both the model and the water are illustrated in figure 10 which shows a time history of the rolling motion of the model in mass condition B_3, the motion of the water in the tanks while the model is in flight, and the natural motion of 3 inches of water in one of the tanks. Evidently there is a coupling between the motions of the model and the water which causes an oscillation of considerably higher frequency than the natural frequency of the water or of the model.

The flight behavior of the model with water in the tanks was considered objectionable by the free-flight-tunnel pilots primarily because the jerky nature of the motions made it difficult to determine when control should be applied to keep the model flying in the test section of the tunnel. It appears from observations of the model in flight tests that the short-period surging motion that would be associated with an airplane affected by fuel sloshing would give a rough ride as well as make the controllability more difficult.

The degree to which the water sloshing affected the lateral motions of the model was found to be related to the relative masses of the water and the model and to the moments of inertia of the model.

The effect of varying the amount of water in the tanks on the motion of the model is illustrated in figures 5 and 6 and in 11 and 12 which compare directly the yawing motions of the model with various amounts of water. Although it may not be clearly evident from the film records, observations of flights for long periods of time showed that the jerky motion caused by the sloshing of the water was most pronounced when there were 2 inches of water in the tanks for the lighter or A loading condition or when there were 3 inches of water in the tanks for the heavier or B loading condition. The degree of jerkiness was approximately the same in these two cases. It was also apparent that increasing the depth of the water from 2 to 3 inches for the A condition and from 3 or 4 inches for the B condition made the effects of the water sloshing slightly less pronounced. Thus the tests indicate that the effects of the water sloshing on the motions of the model were most pronounced when the tanks were less than half full (approximately one-seventh to one-third full by volume, depending on the mass of the model).

It was found that increasing the mass of the model caused the effect of the sloshing of the water on the lateral motions of the model to be less pronounced. This result can be seen by comparison of conditions A with B (figs. 5 and 6, 11 and 12, or more clearly fig. 13) or C with D (figs. 7 and 8).

Increasing the yawing moment of inertia of the basic model (conditions B to C) caused the period of the short-period jerky motion of the model to become shorter and the amplitude of the yawing motion to become larger as can be seen from figure 14 or from comparison of figures 6 and 7. This increase in moment of inertia also caused the general flight behavior of the model to become worse. No tests were made with 3 or 4 inches of water for condition C because of the general difficulty of flying the model.

It appeared from observations of the model in flight tests with water in the tanks that there was a short-period surging in the airspeed of the model which was similiar to the high-frequency lateral oscillations and appeared to have about the same period as these lateral motions (0.2 to 0.3 second). This result is illustrated by figure 15 which shows a time history of the pitching, forward displacement and airspeed of the model in mass condition A_3. The characteristics of this motion were generally similiar to those of the lateral motions and the effects of varying the mass of the water or mass of the model were about the same.

CONCLUSIONS

The results of an investigation made in the Langley free-flight tunnel to determine the effects of the sloshing of water in the partly filled, unbaffled, spherical tanks on the lateral stability of a flying model for conditions where the natural period of the model was greater than the natural period of the water may be summarized as follows:

1. The sloshing of water in the tanks caused the model to have erratic lateral motions in the form of small-amplitude, high-frequency lateral oscillations.

2. The most pronounced effect of the water sloshing on the motions of the model occurred when the tanks were less than half full (between one-seventh and one-third full by volume depending on the mass of the model).

3. For a given amount of water in the tanks, increasing the empty weight of the model caused a decrease in the effect of the water sloshing on the lateral motions.

4. Increasing the yawing moment of inertia caused the effects of the water sloshing on the yawing motions to become more pronounced but there was little effect on the rolling or sidewise motions.

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REFERENCE

1. Shortal, Joseph A., and Osterhout, Clayton J.: Preliminary Stability and Control Tests in the NACA Free-Flight Wind Tunnel and Correlation with Full-Scale Flight Tests. NACA TN No. 810, 1941.

TABLE I

MASS CHARACTERISTICS OF THE MODEL FOR THE VARIOUS TEST CONDITIONS

Condition[1]	Weight			I_X (slug-ft^2)	I_Y (slug-ft^2)	I_Z (slug-ft^2)
	Empty weight (lb)	Weight of water (lb)	Gross weight (lb)			
A_0	7.05	0	7.05	0.0900	0.1527	0.1985
A_2	7.05	3.02	10.07	.1034	.1661	.2089
A_3	7.05	6.14	13.19	.1084	.1711	.2197
B_0	11.25	0	11.25	.0924	.1556	.1993
B_2	11.25	3.02	14.27	.1058	.1690	.2098
B_3	11.25	6.14	17.39	.1109	.1741	.2206
B_4	11.25	9.70	20.95	.1077	.1709	.2329
C_0	10.30	0	10.30	.1173	.4658	.5333
C_2	10.30	3.02	13.32	.1307	.4792	.5438
D_0	14.90	0	14.90	.1188	.4658	.5352
D_2	14.90	3.02	17.92	.1332	.4817	.5467

[1]Numerical subscripts indicate depth of water in the tanks in inches.

TABLE II

DIMENSIONAL CHARACTERISTICS OF THE MODEL

Wing:	
Area, sq ft	2.67
Span, ft	4.0
Aspect ratio	6.0
Mean aerodynamic chord	0.70
Sweepback of 25-percent-chord line, deg	0
Dihedral, deg	0
Taper ratio (ratio of tip chord to root chord)	0.5
Root chord, ft	0.90
Tip chord, ft	0.45
Incidence, deg	10
Horizontal tail:	
Area, sq ft	0.544
Area, percent of wing area	20.00
Aspect ratio	4.00
Taper ratio (ratio of tip chord to root chord)	0.5
Incidence, deg	10
Elevator:	
Area, sq ft	0.206
Area, percent of horizontal-tail area	37.6
Vertical tail:	
Area, sq ft	0.4005
Area, percent of wing area	15
Taper ratio (ratio tip chord to root chord)	0.5

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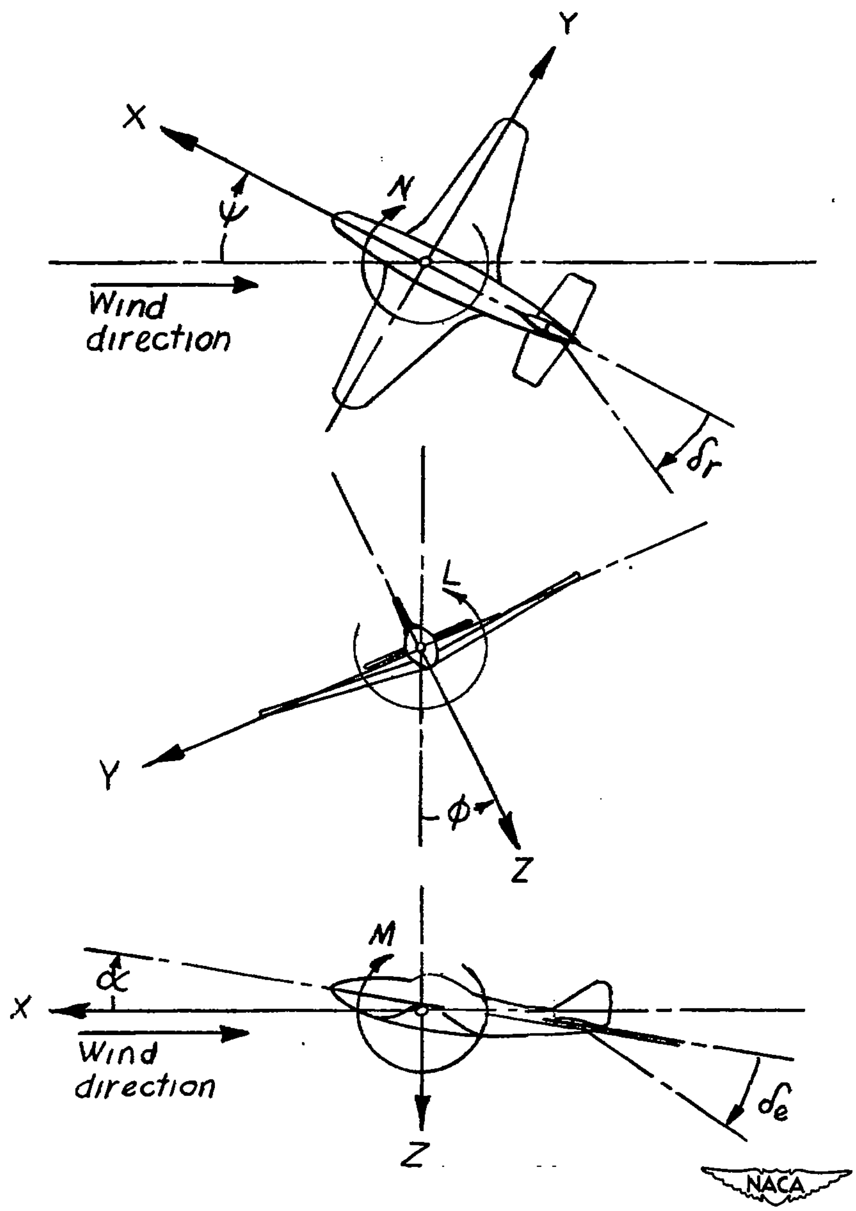


Figure 1.- The stability system of axes. Arrows indicate positive directions of moments, forces, and control-surface deflections. This system of axes is defined as an orthogonal system having the origin at the center of gravity and in which the Z-axis is in the plane of symmetry and perpendicular to the relative wind, the X-axis is in the plane of symmetry and perpendicular to the Z-axis, and the Y-axis is perpendicular to the plane of symmetry.

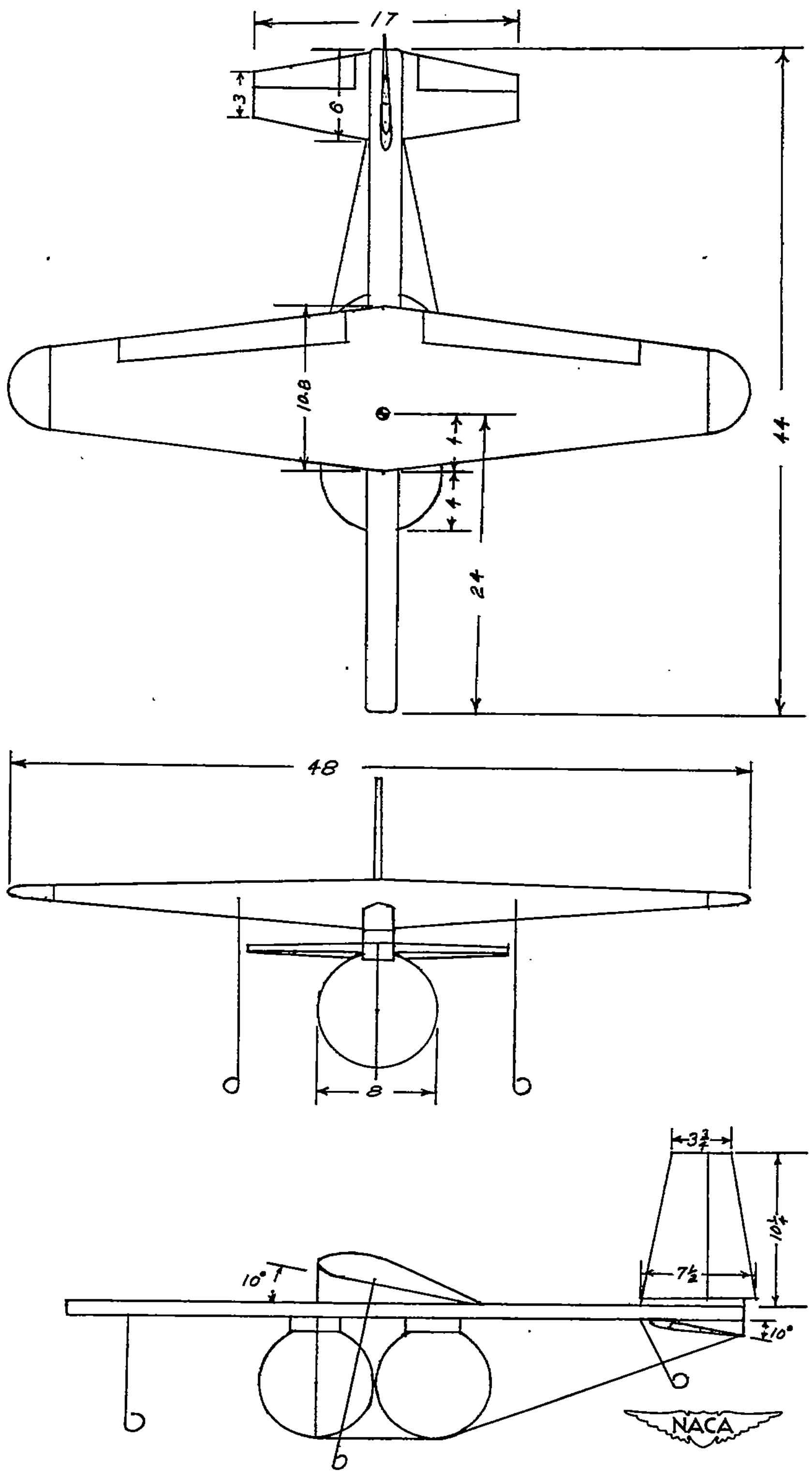
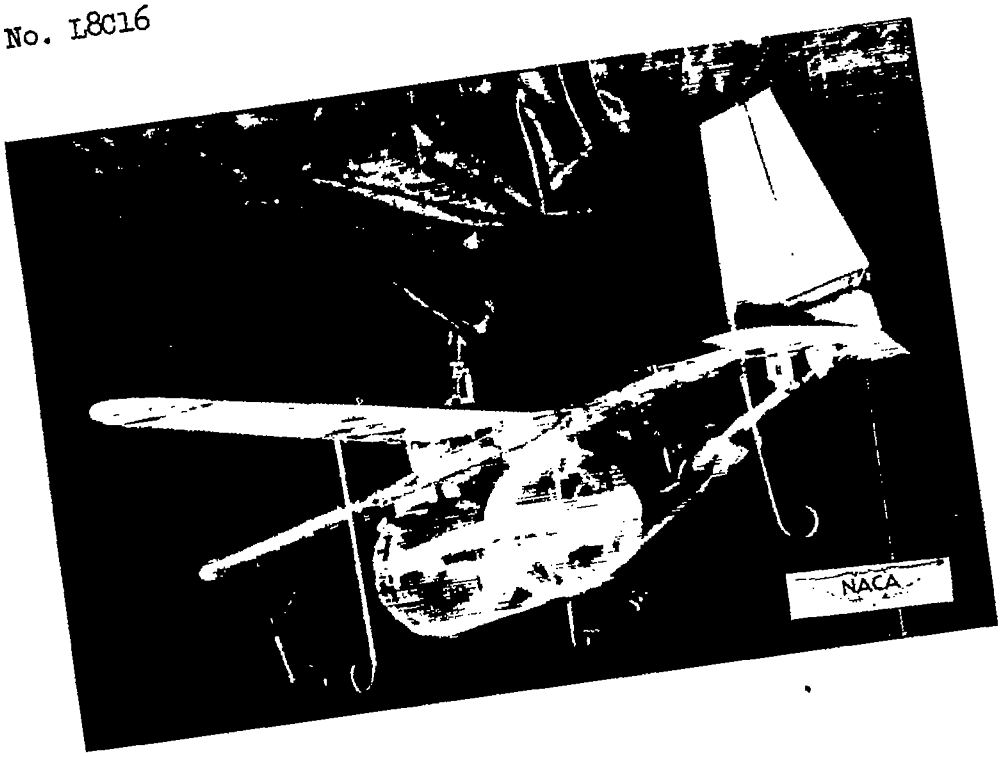


Figure 2.- Three-view sketch of the model used in the fuel-sloshing investigation. Dimensions are in inches.



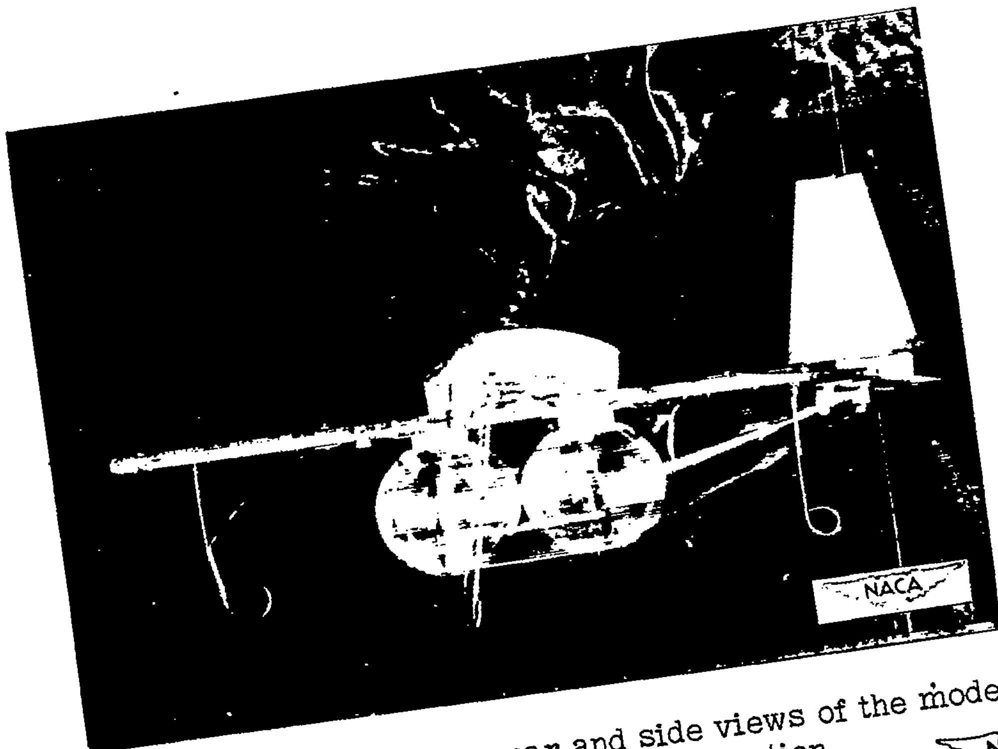


Figure 3(a).- Three-quarter-rear and side views of the model used in the fuel-sloshing investigation.

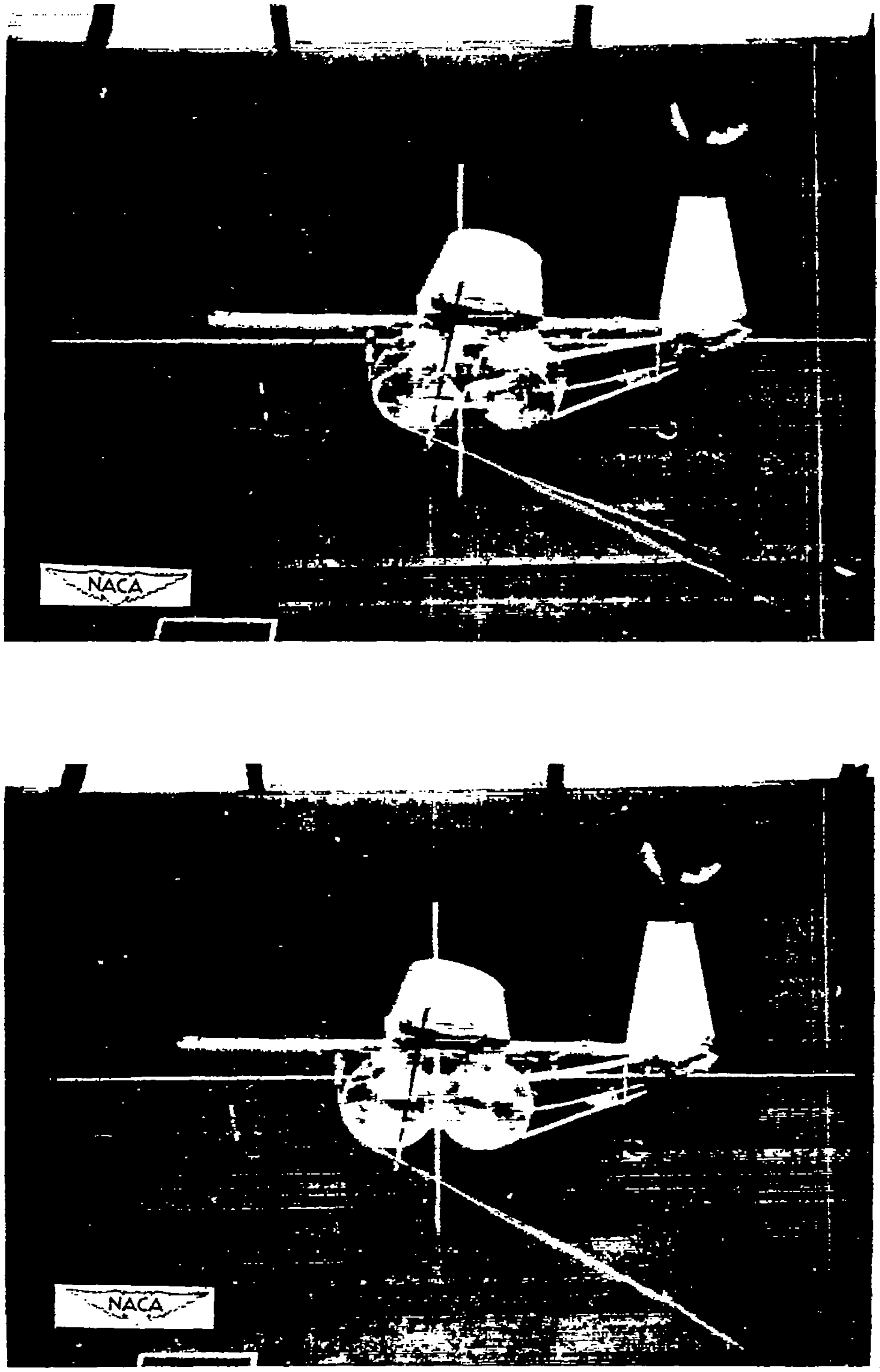


Figure 3(b).- Side views of the model in flight with three inches of water sloshing in the tanks.

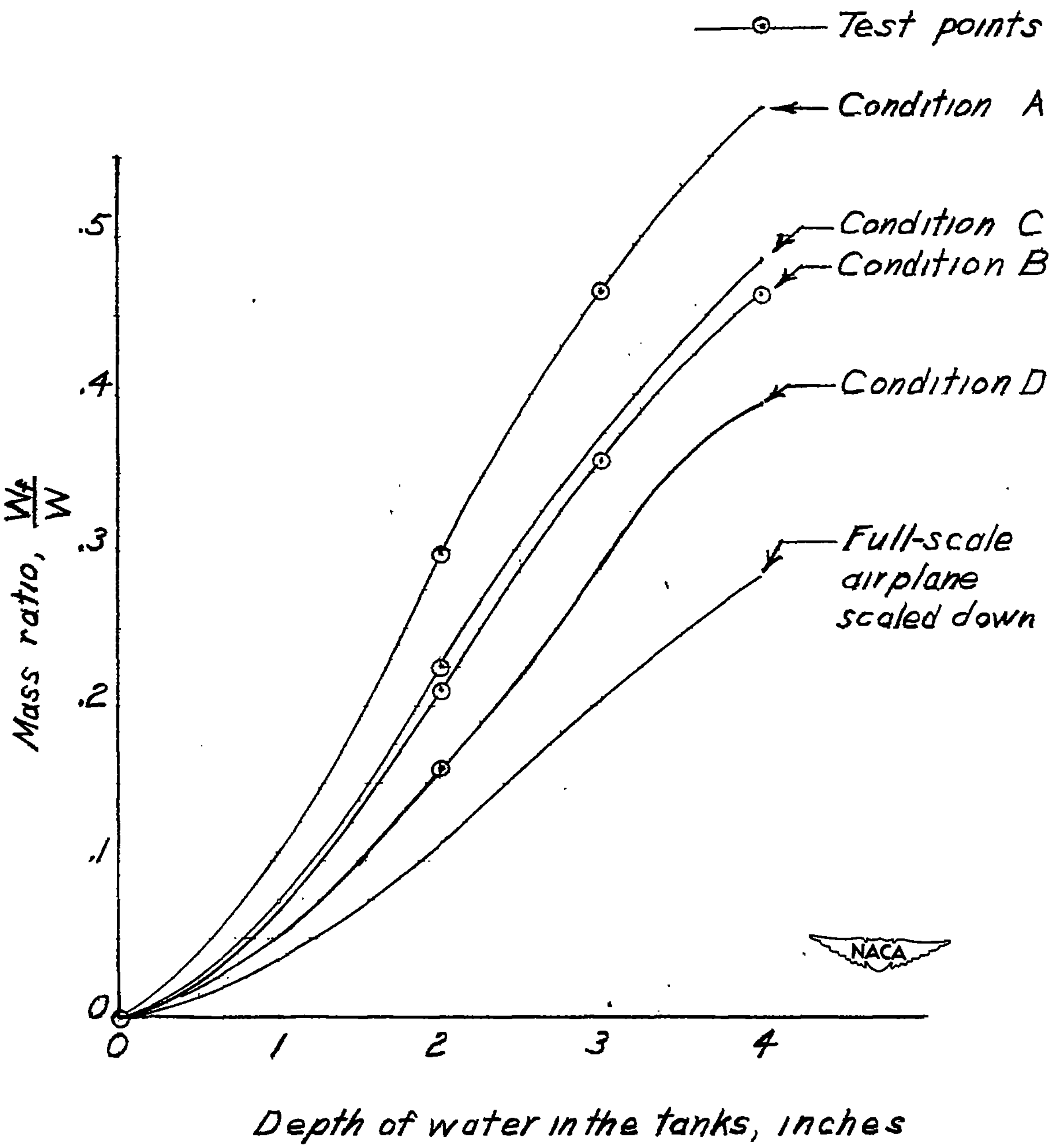


Figure 4.- Variation of mass ratio with depth of water in tanks.

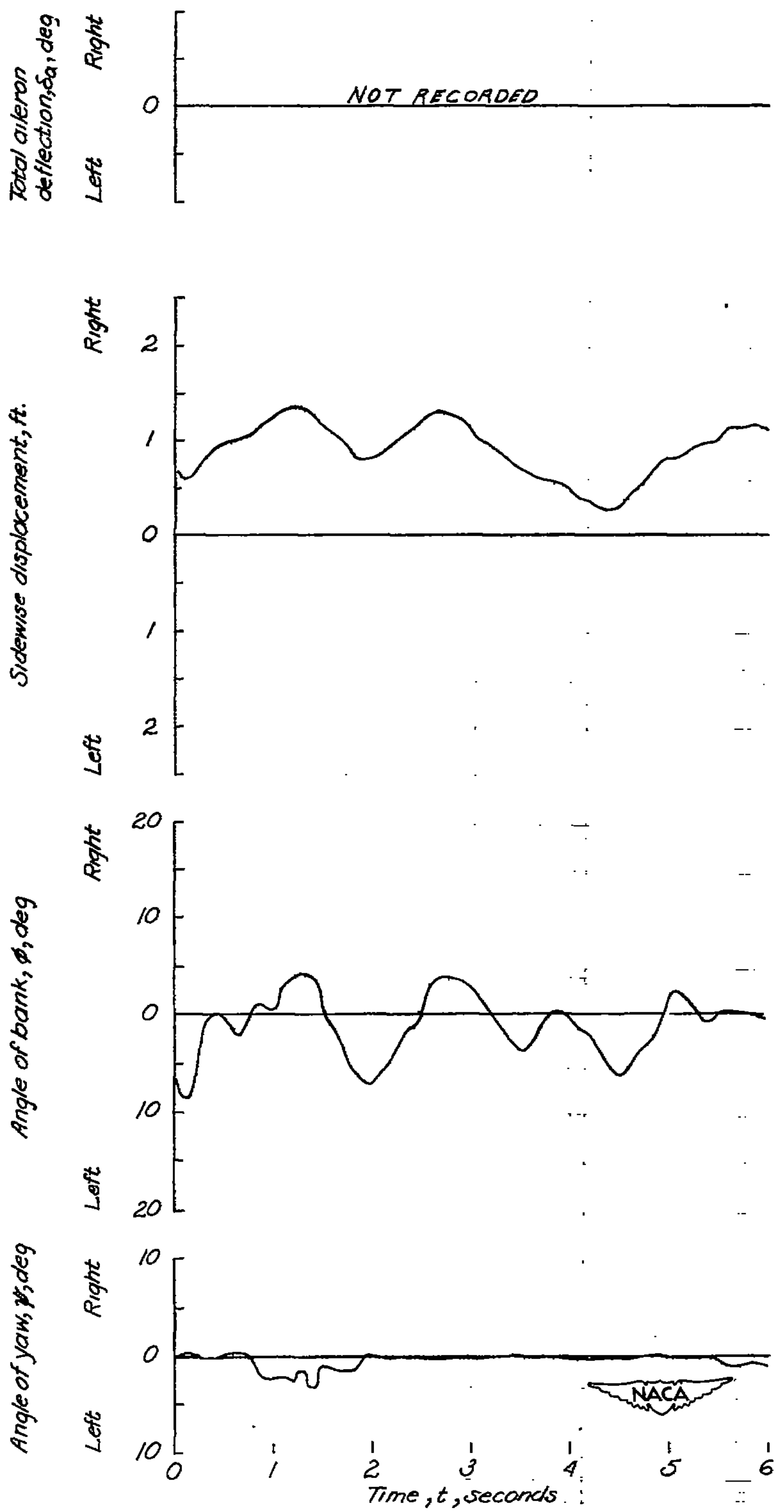


Figure 5(a).- Time histories of the lateral motions of the model for mass condition A_0.

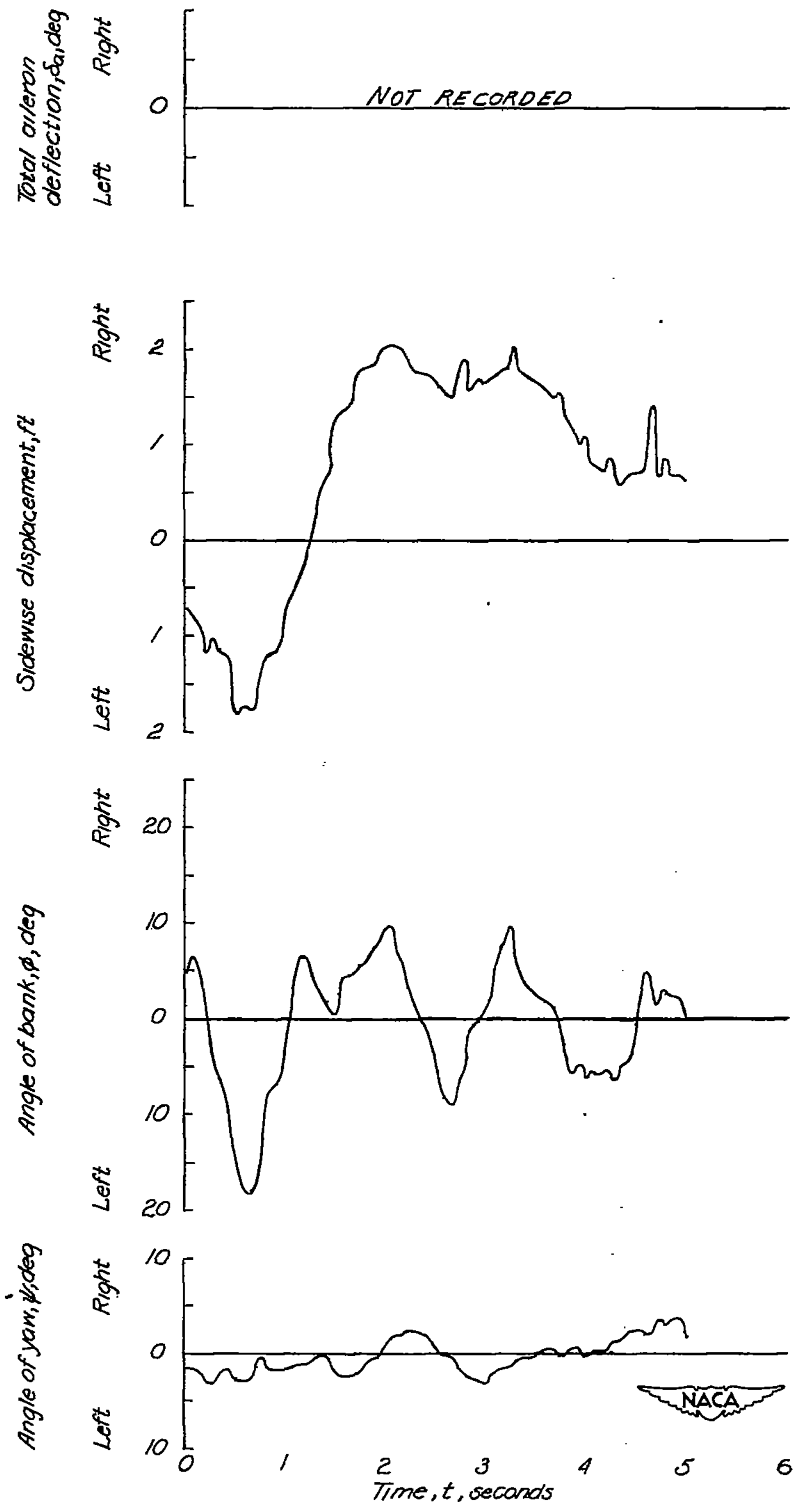


Figure 5(b).- Time histories of the lateral motions of the model for mass condition A_2.

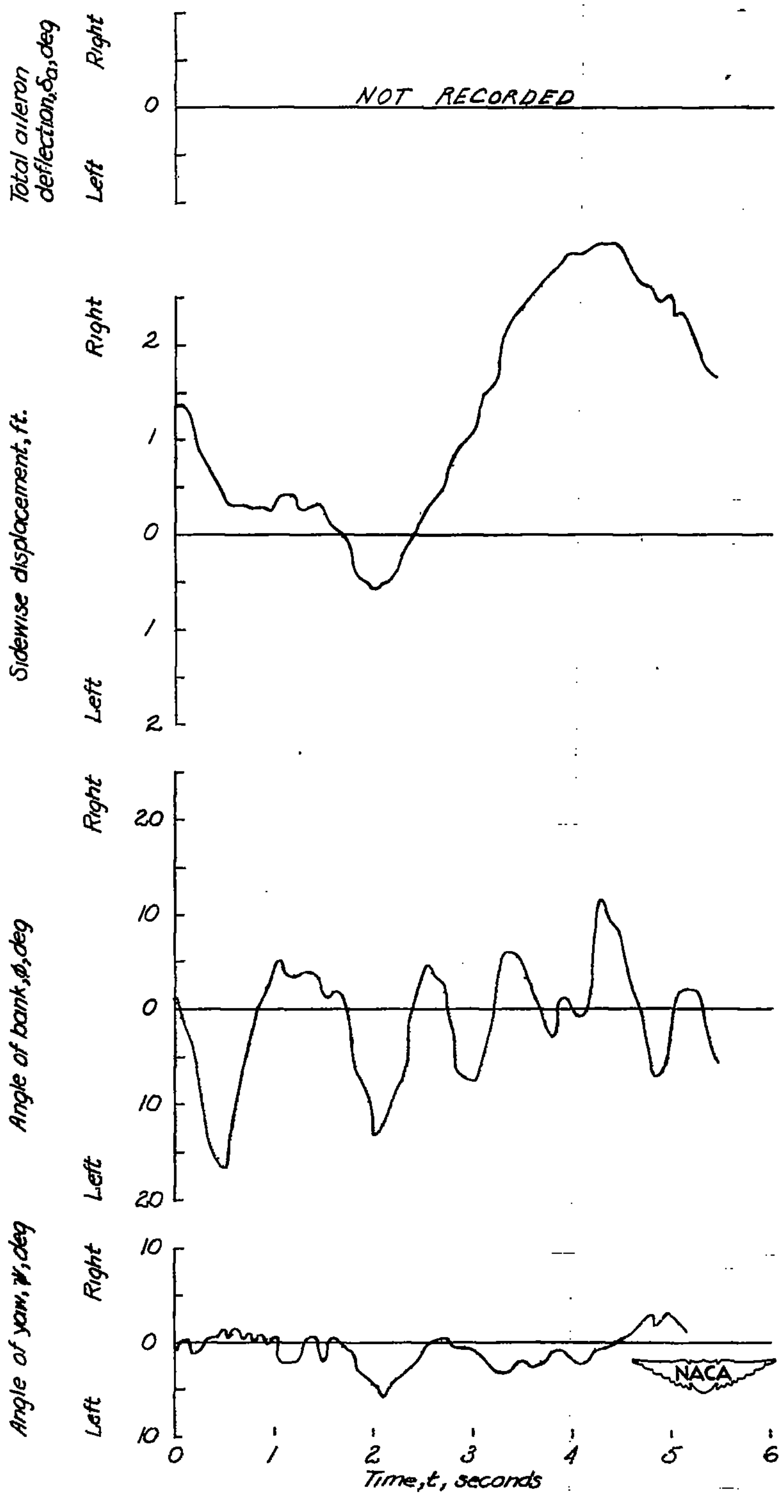


Figure 5(c).- Time histories of the lateral motions of the model for mass condition A_3.

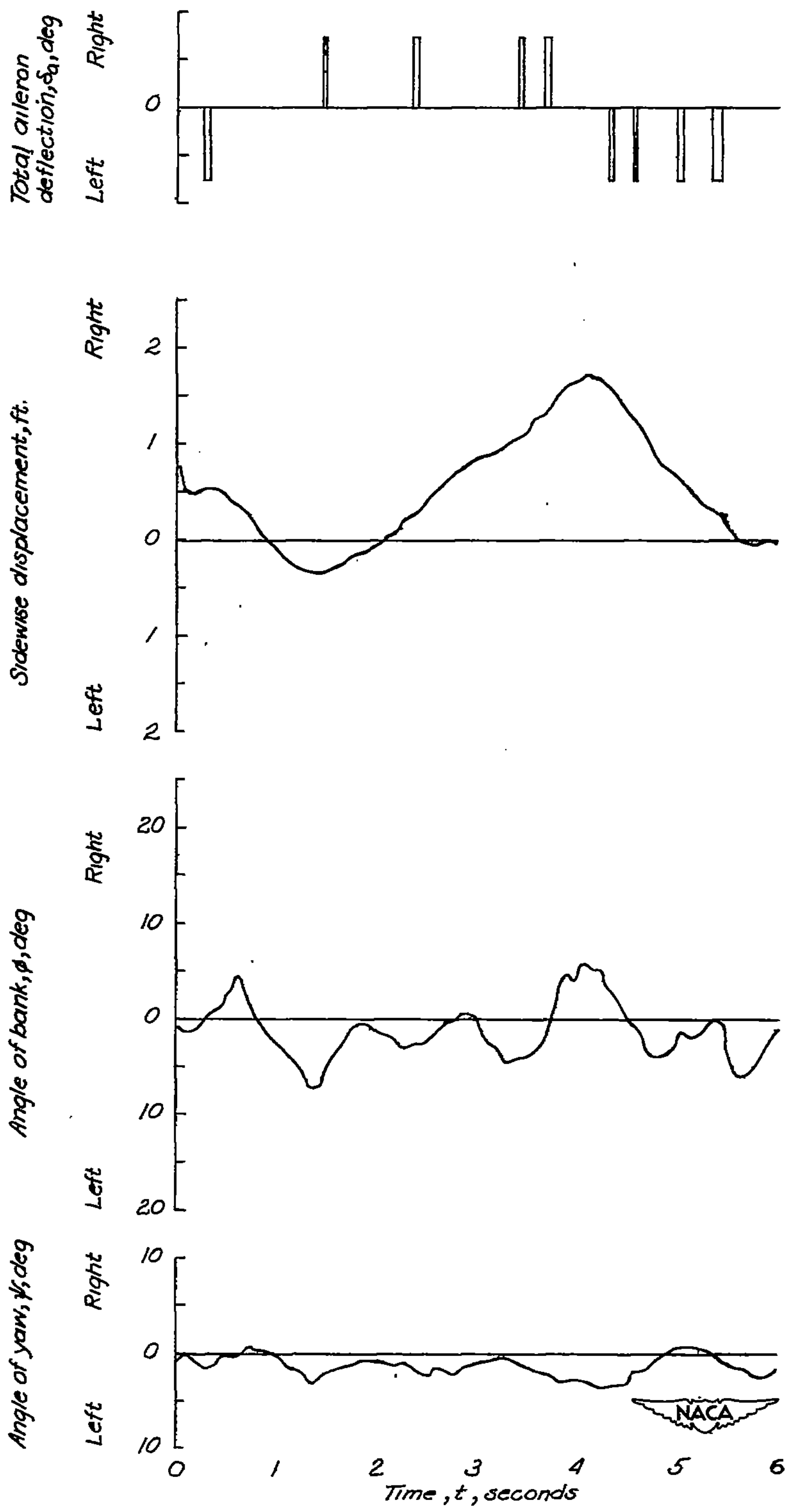


Figure 6(a).- Time histories of the lateral motions of the model for mass condition B_0.

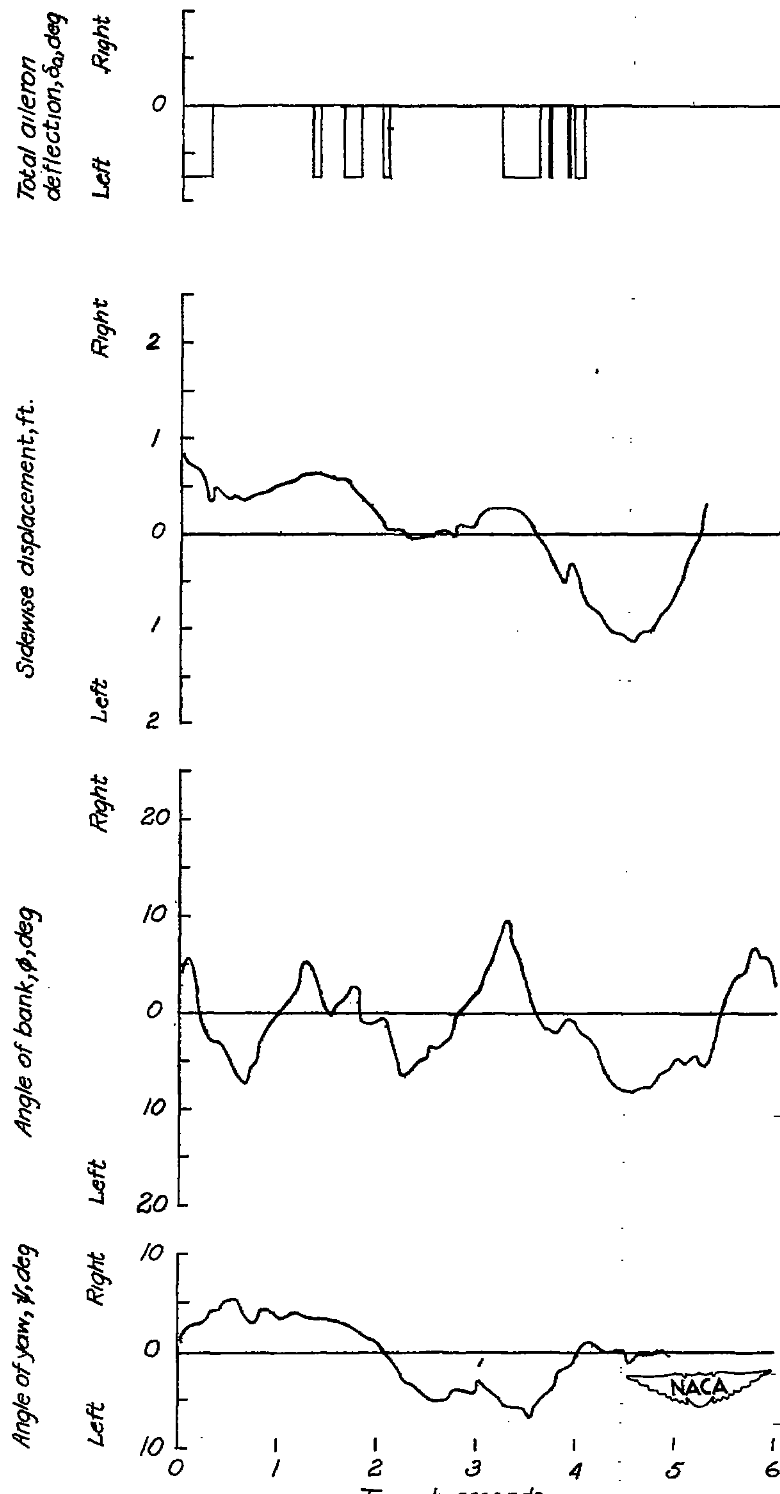


Figure 6(b).- Time histories of the lateral motions of the model for mass condition B_2.

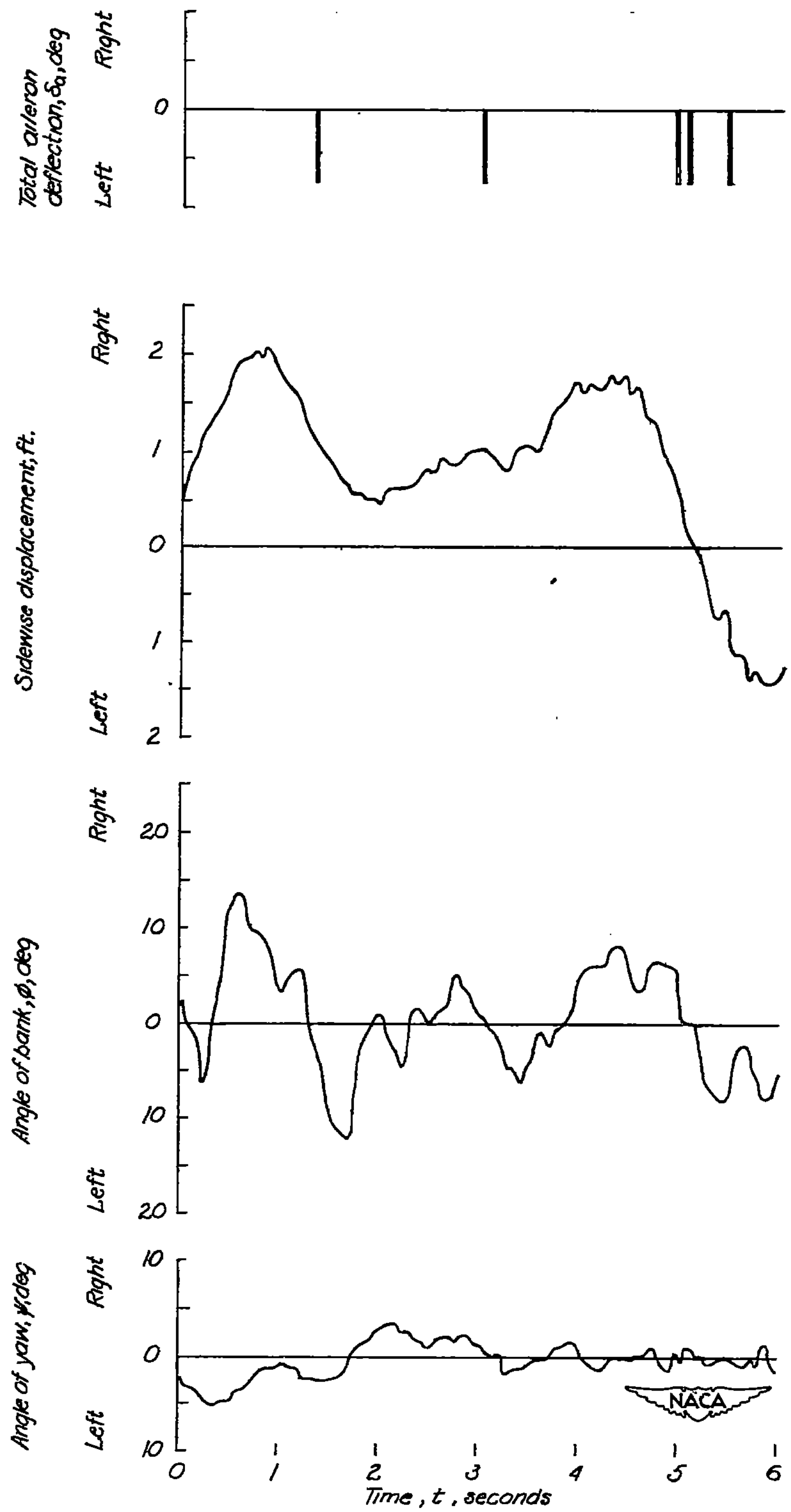


Figure 6(c).- Time histories of the lateral motions of the model for mass condition B_3.

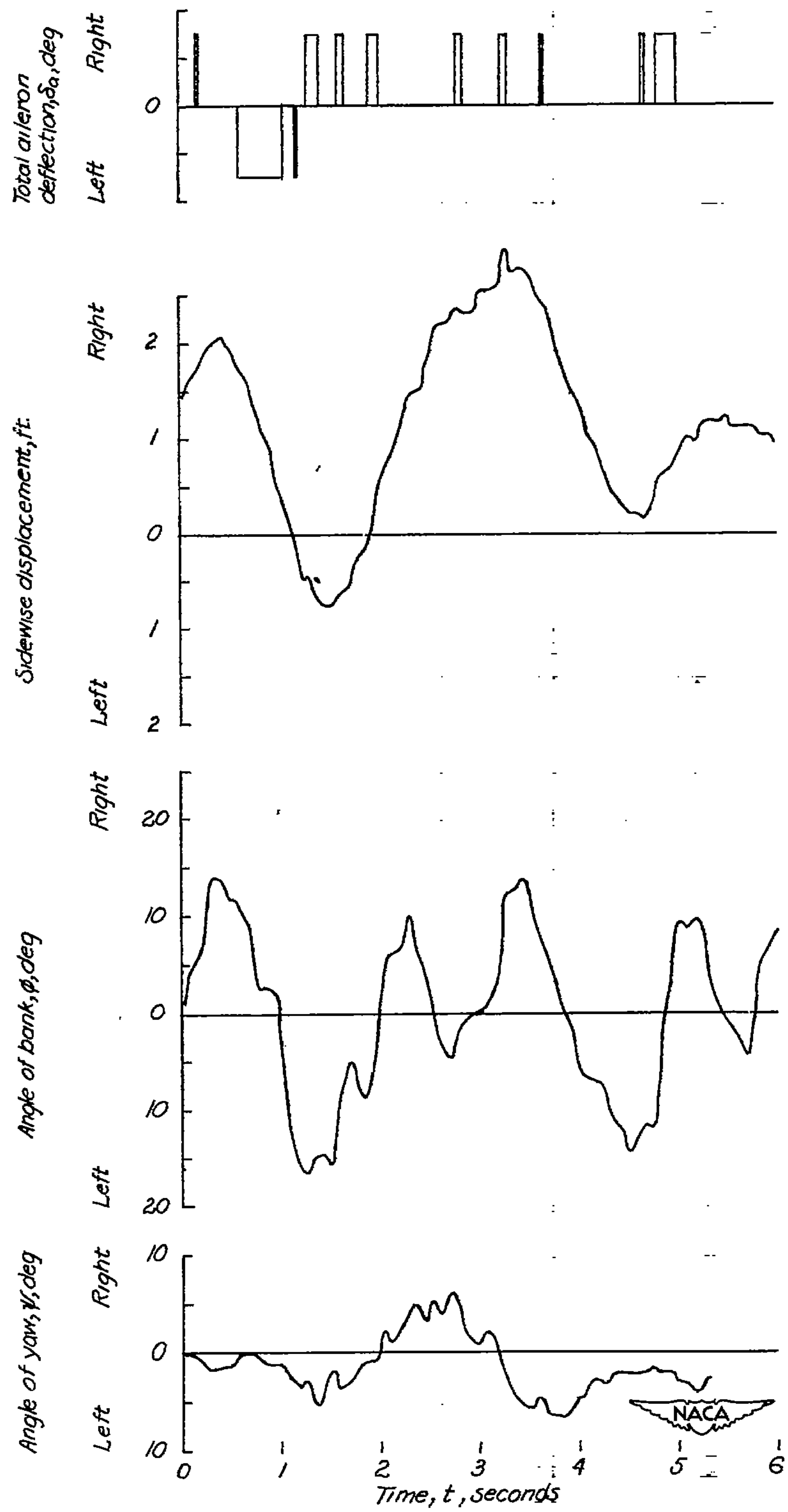


Figure 6(d).- Time histories of the lateral motions of the model for mass condition B_4.

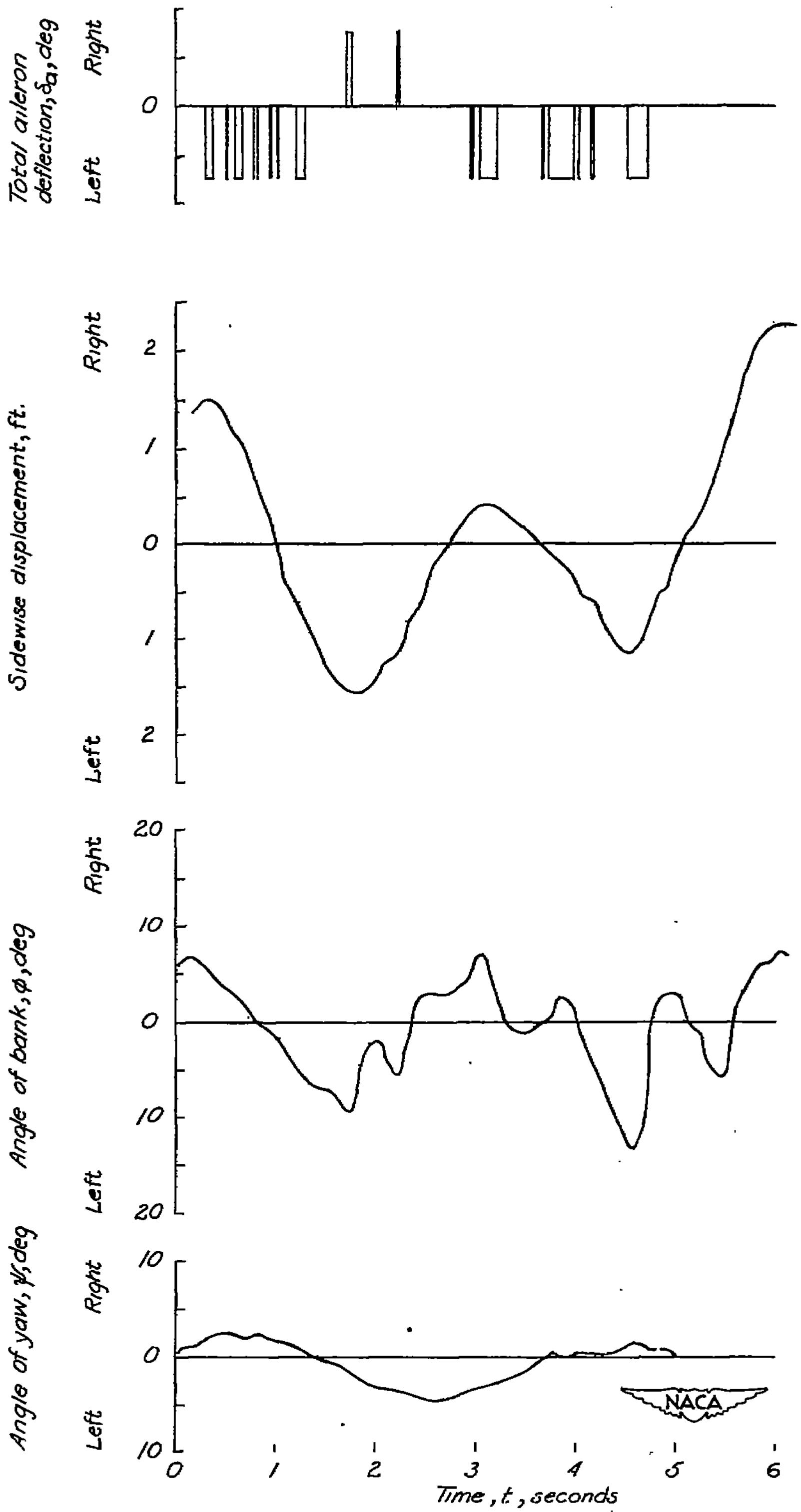


Figure 7(a).- Time histories of the lateral motions of the model for mass condition C_0.

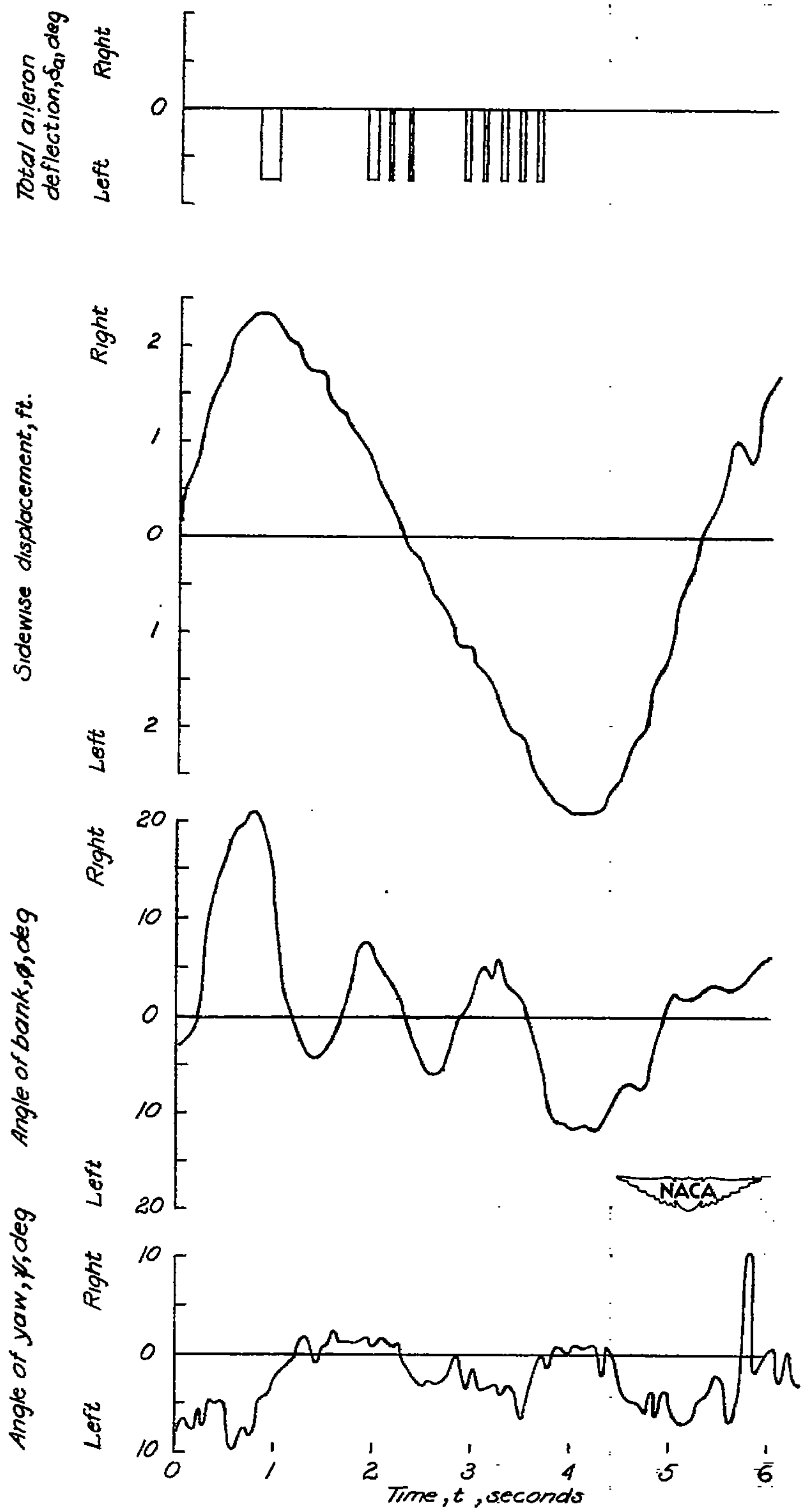


Figure 7(b).- Time histories of the lateral motions of the model for mass condition C_2.

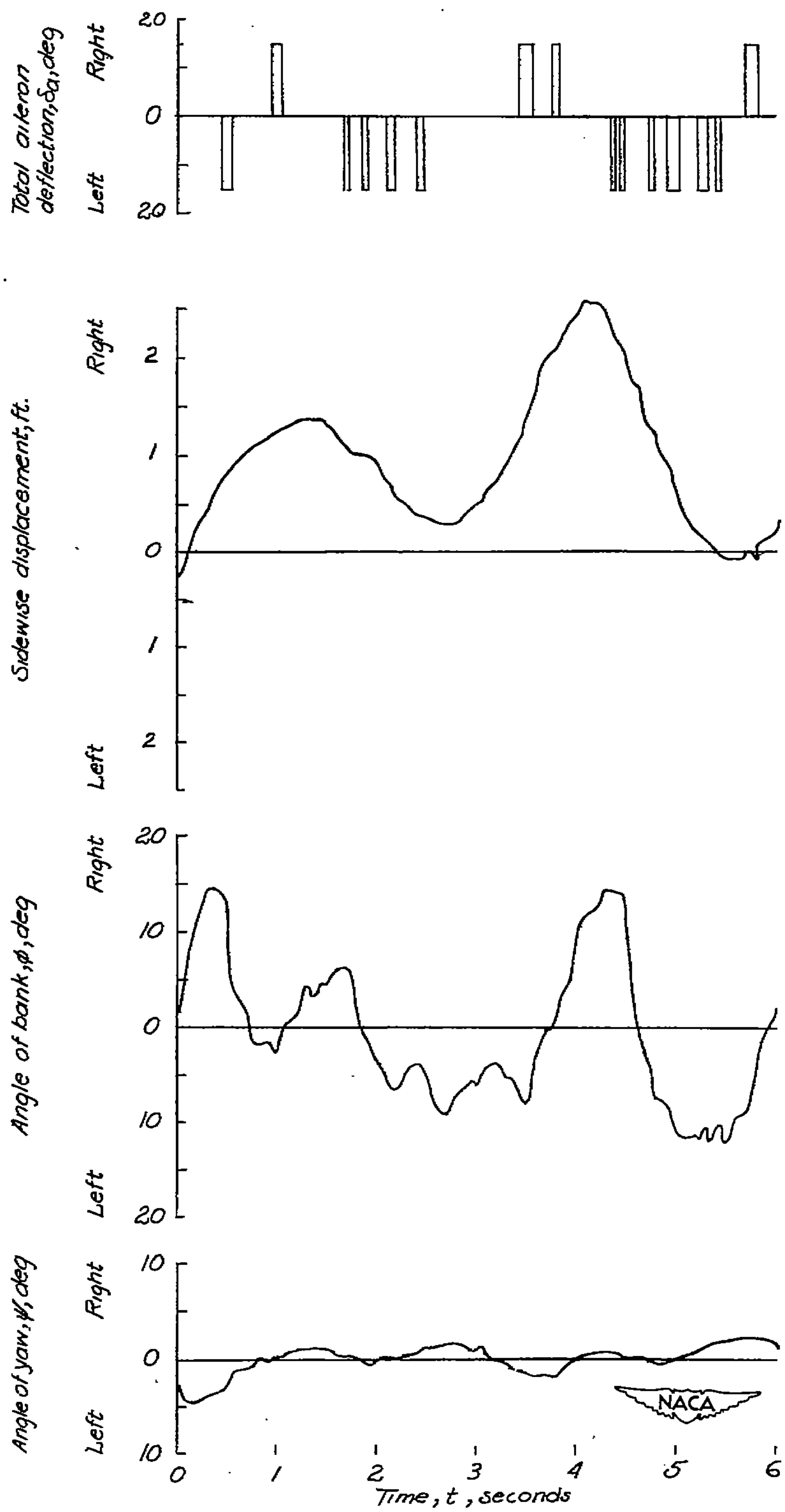


Figure 8(a).- Time histories of the lateral motions of the model for mass condition D_0.

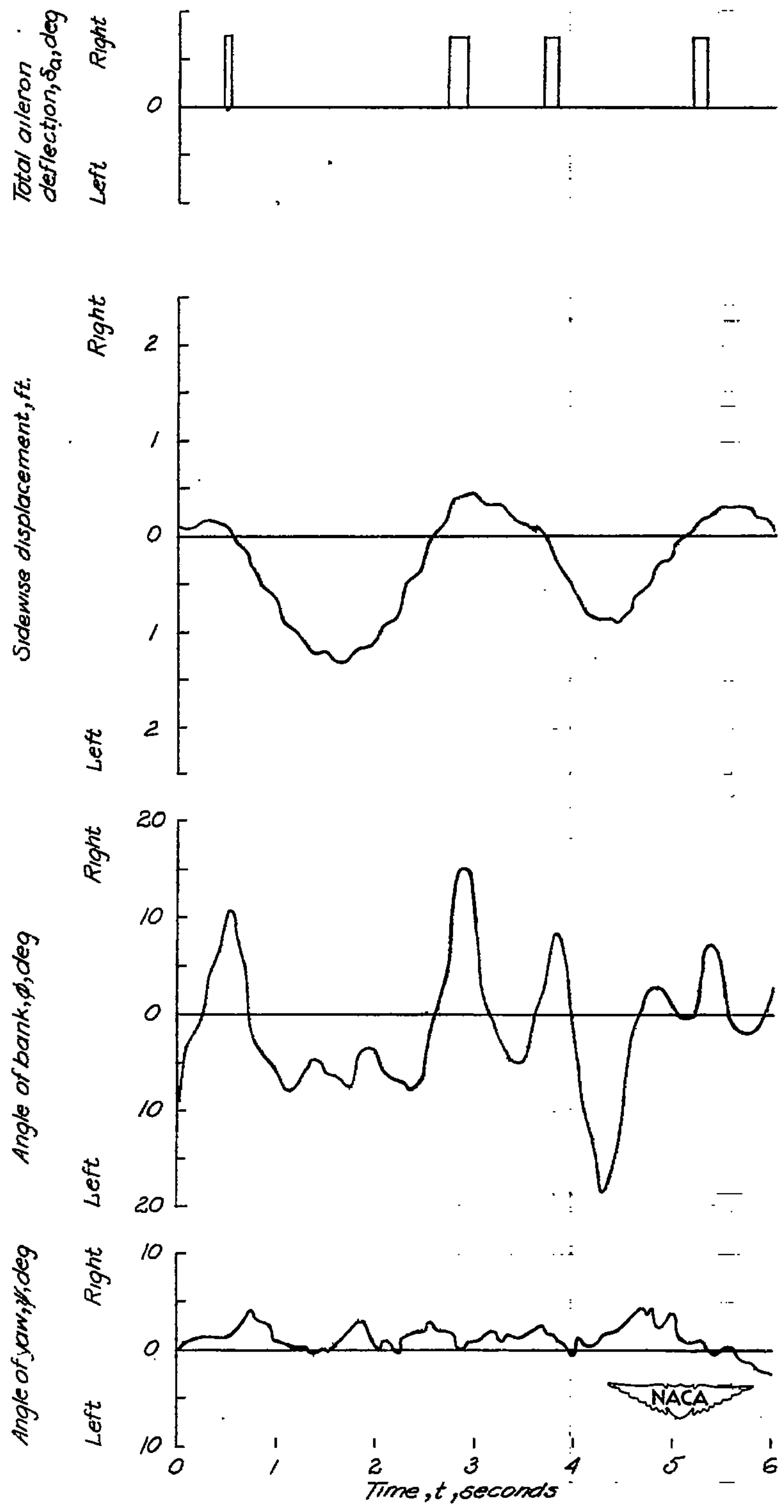


Figure 8(b).- Time histories of the lateral motions of the model for mass condition D_2.

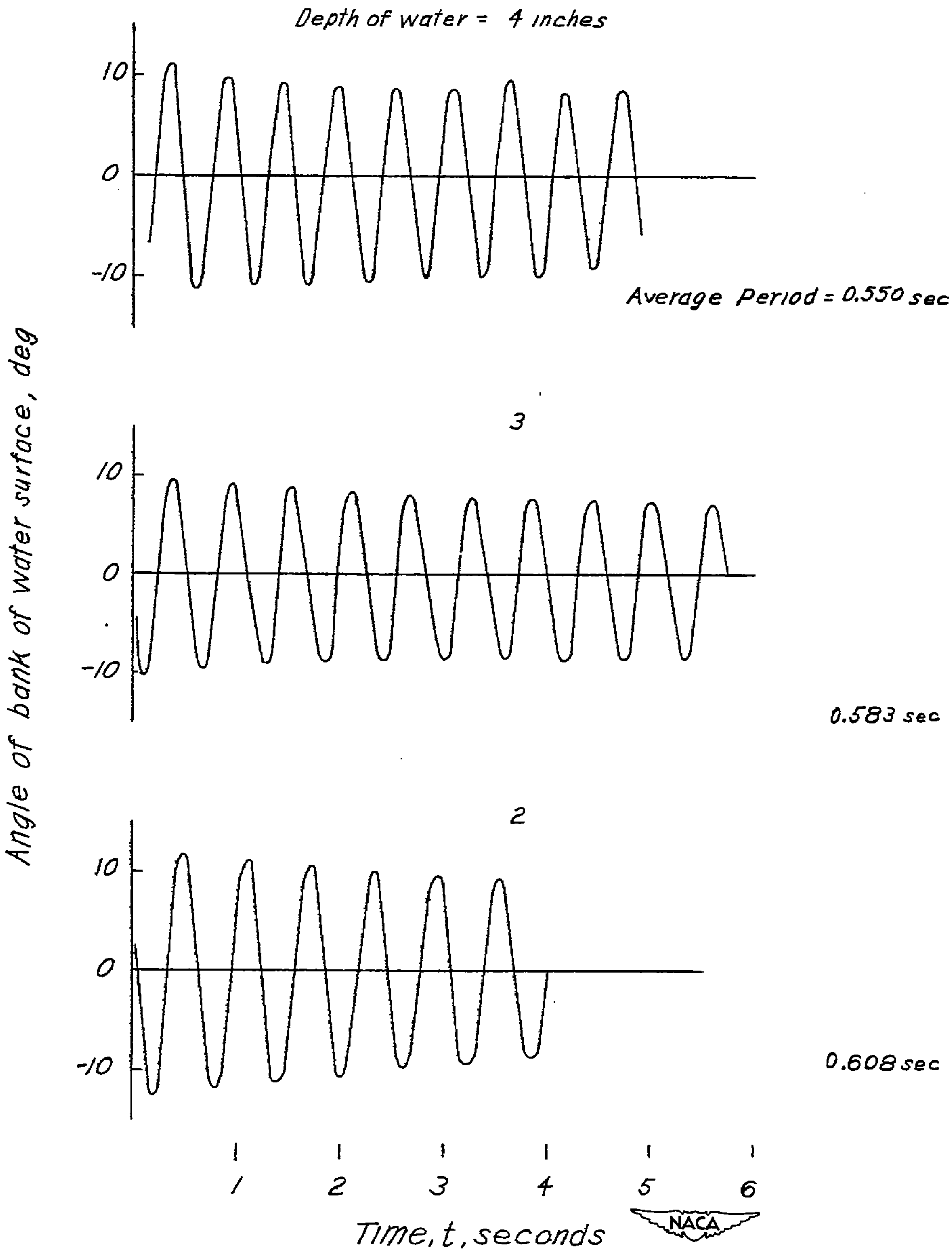


Figure 9.- Time histories of the natural motion of two, three, and four inches of water in the tanks following a disturbance.

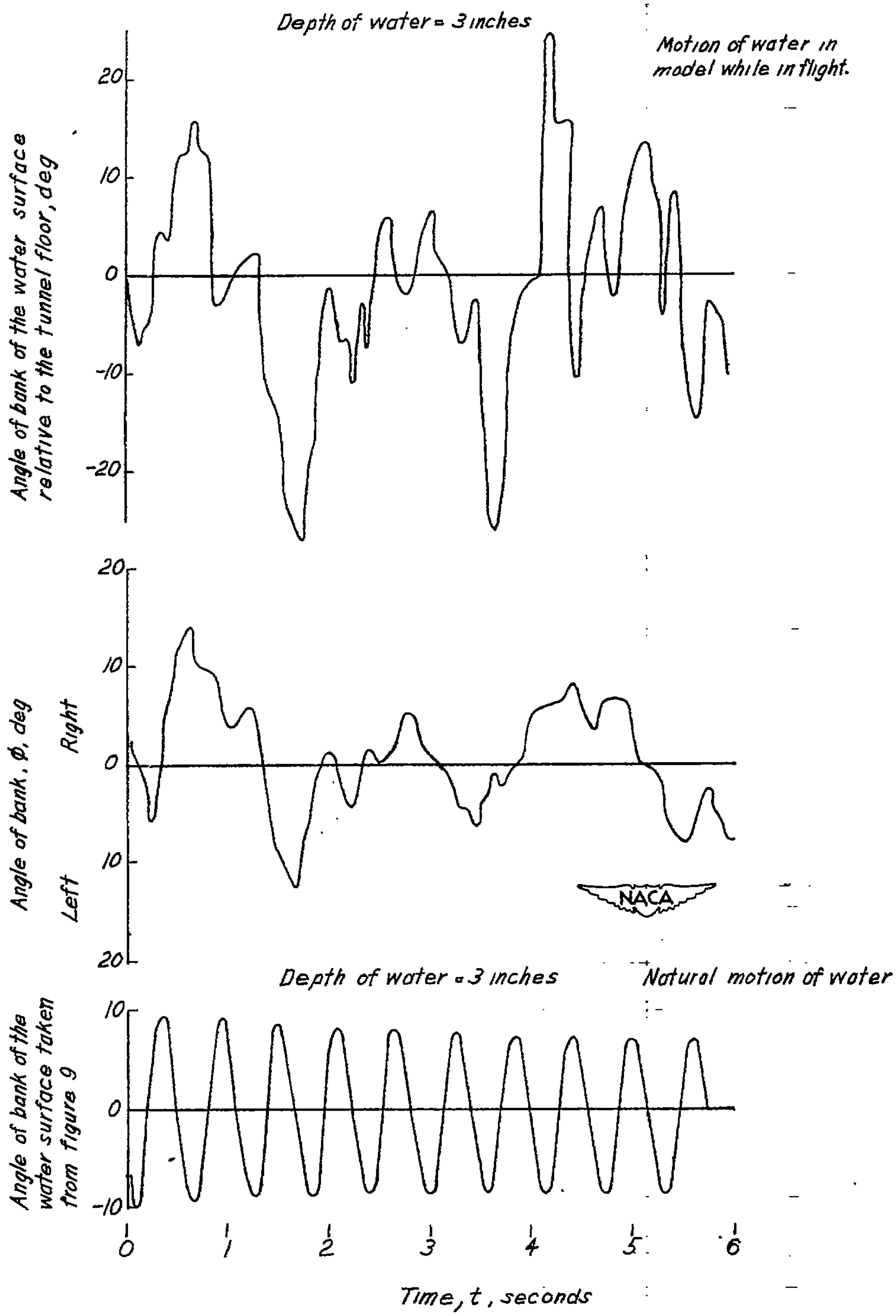


Figure 10.- Time histories of the rolling motion of the model in mass condition B_3, the motion of the water in the tanks while the model is in flight, and the natural motion of three inches of water in one of the tanks.

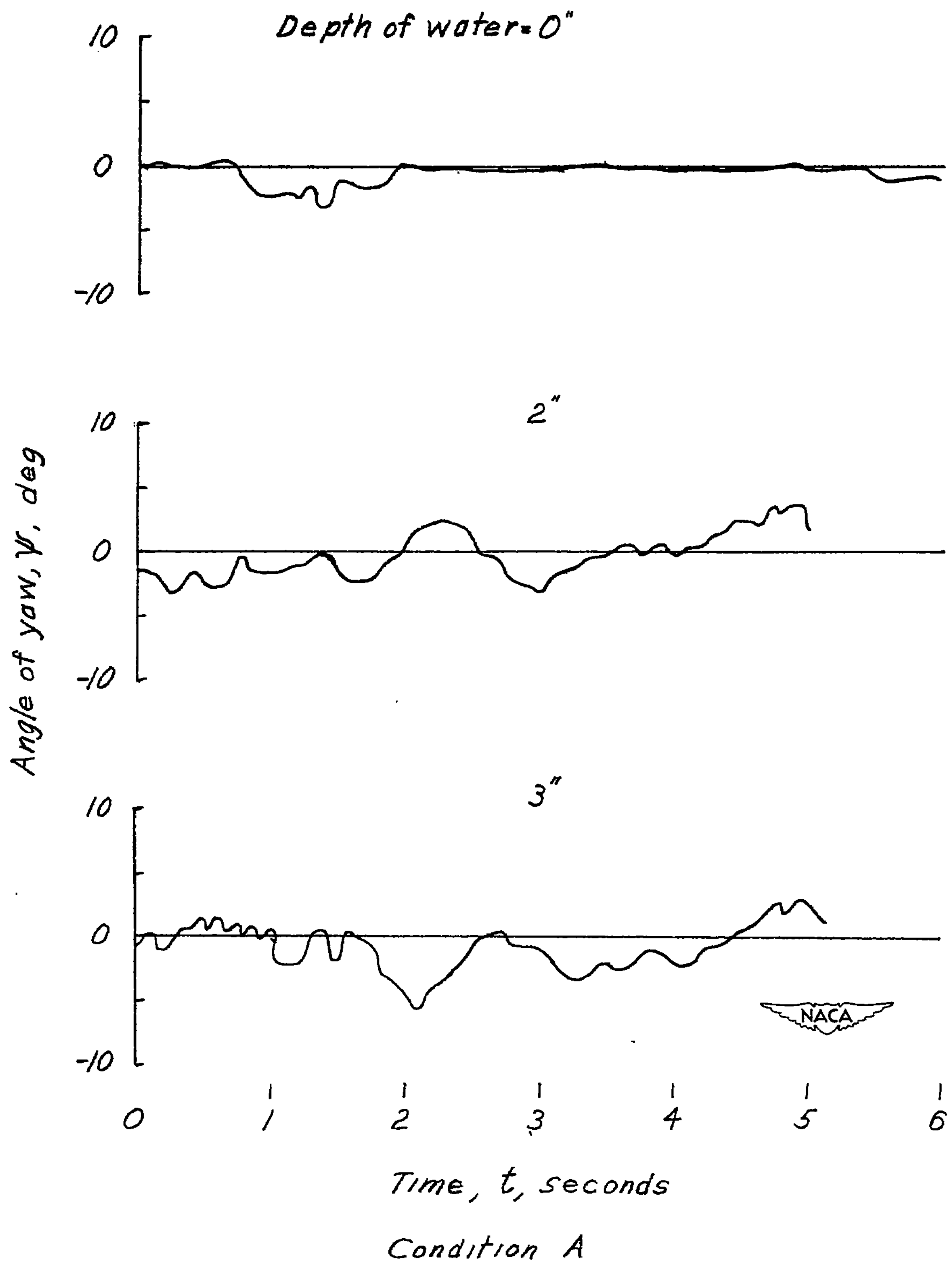


Figure 11.- The effect of varying the depth of water in the tanks on the yawing motions of the model for mass condition A.

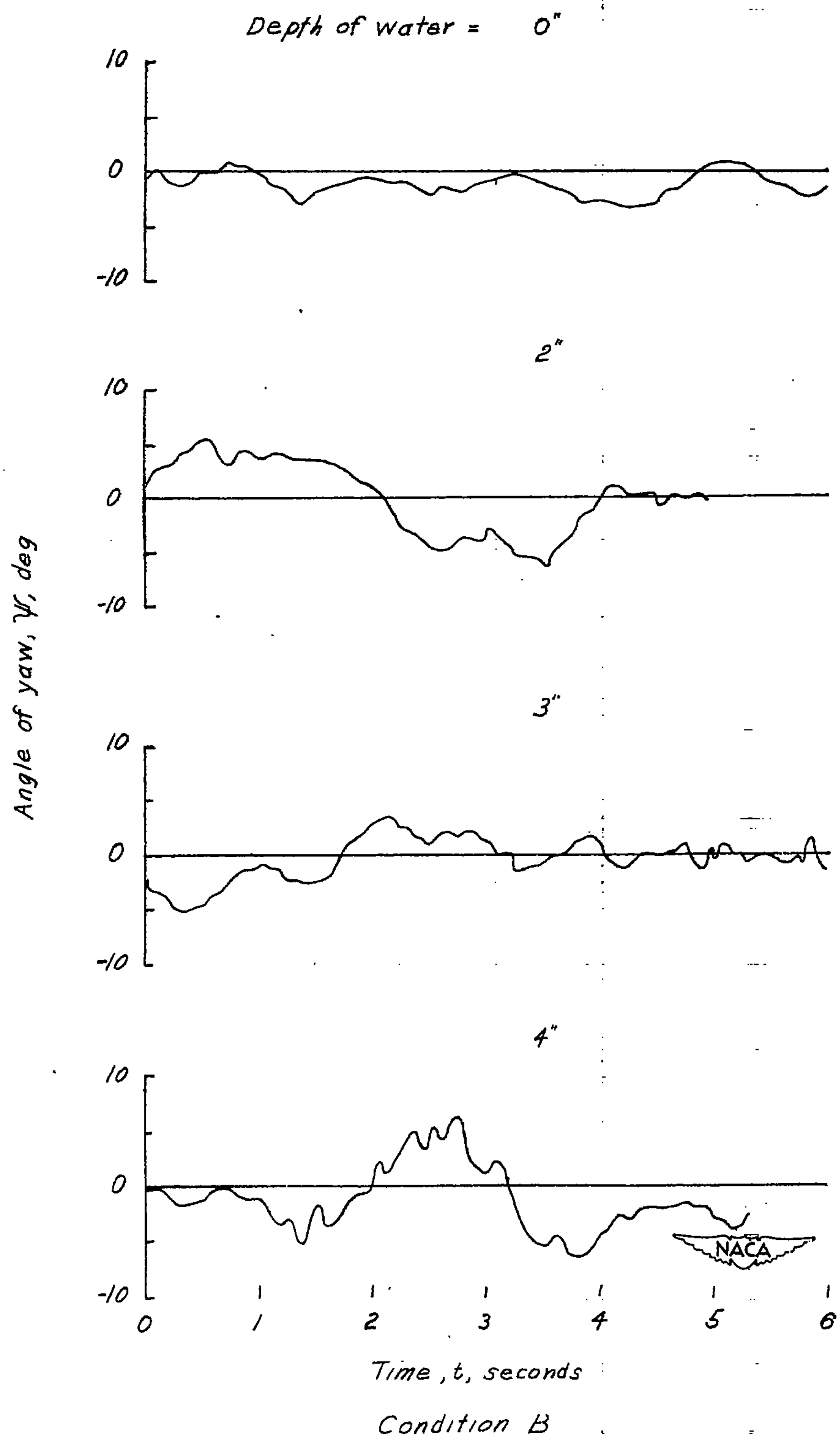


Figure 12.- The effect of varying the depth of water in the tanks on the yawing motions of the model for mass condition B.

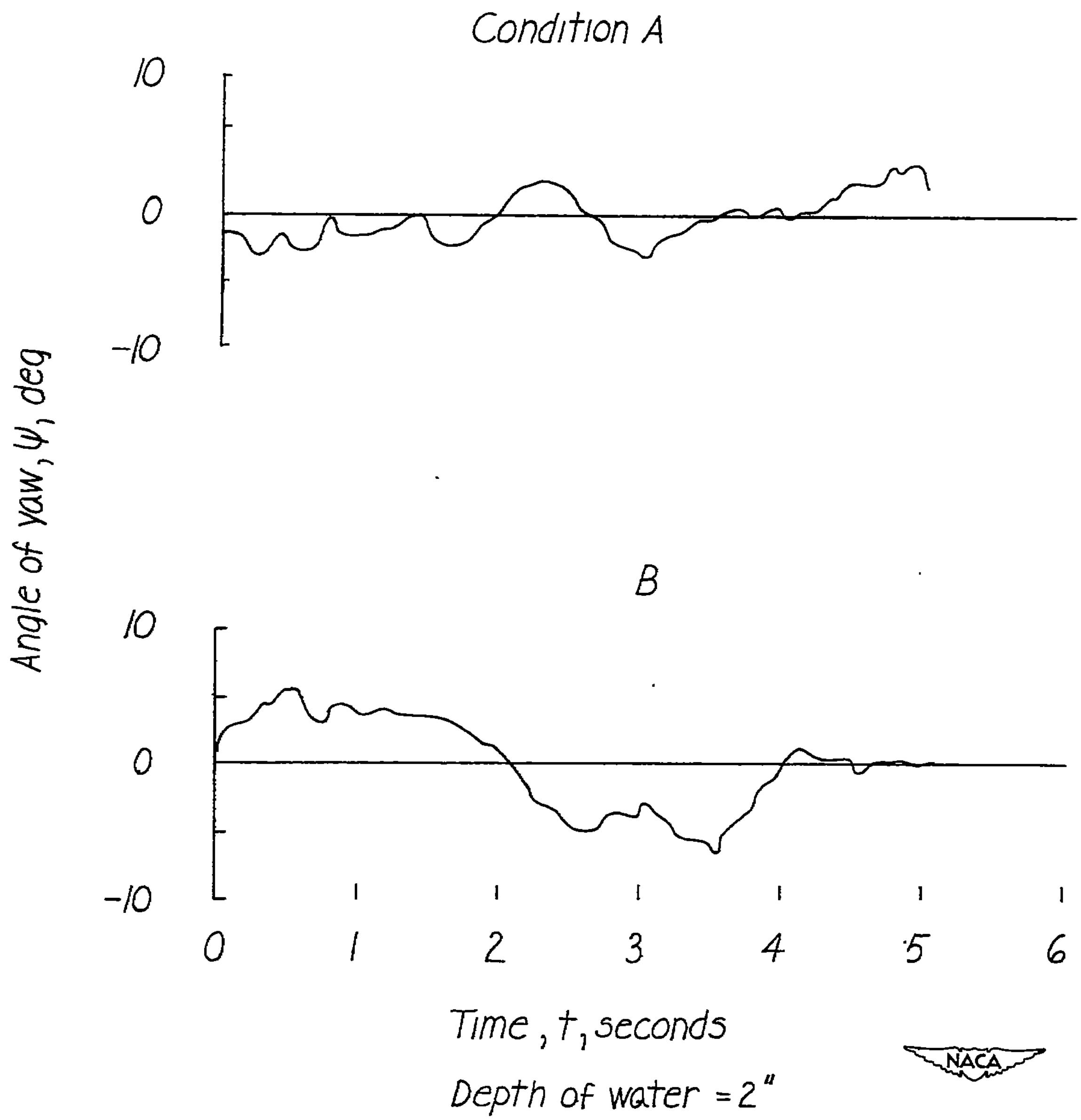


Figure 13.- The effect of varying the mass of the model on the effects of the water sloshing. The depth of water held constant at two inches.

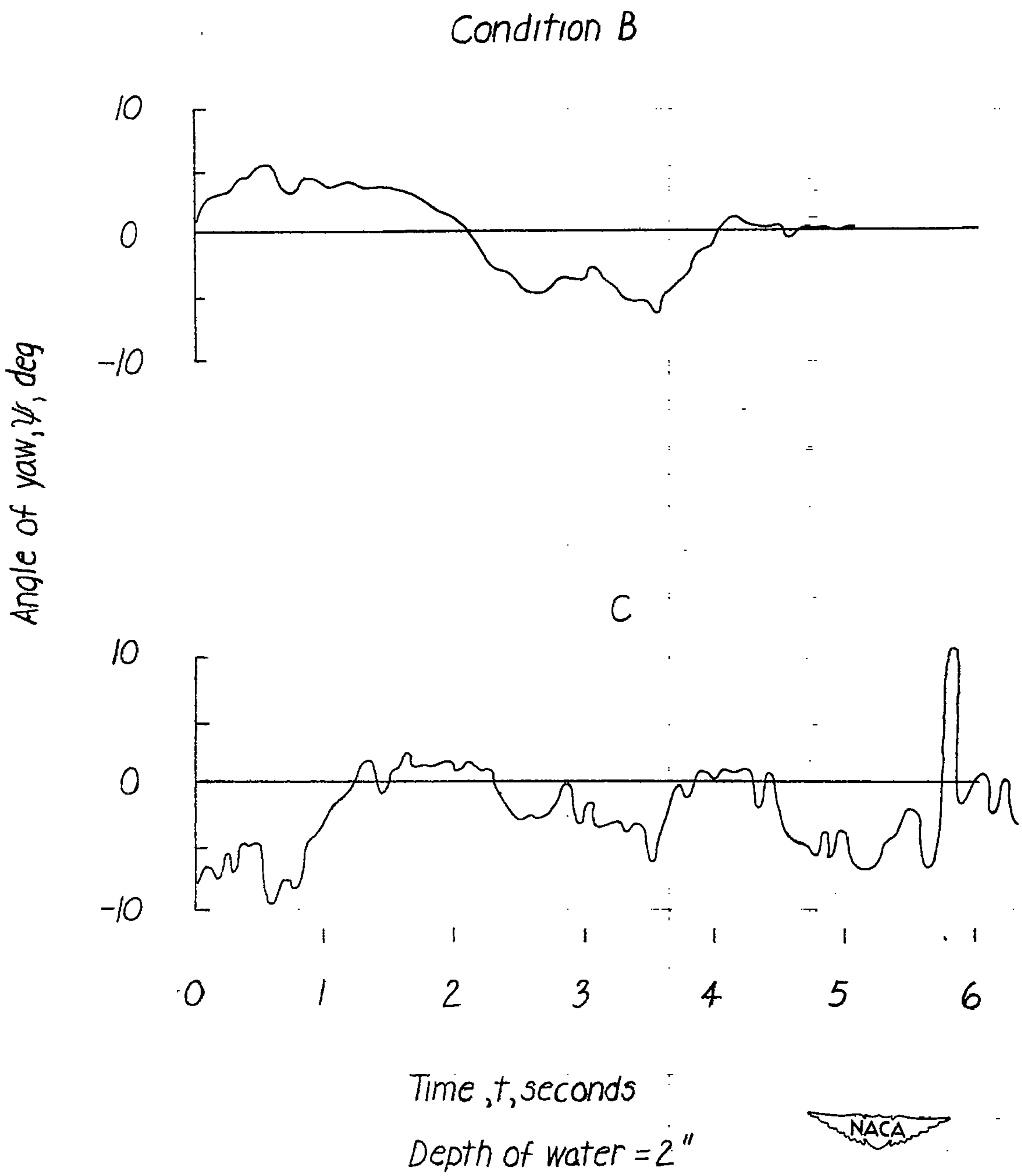


Figure 14.- The effect of varying the moment of inertia of the model on the effects of the water sloshing. The depth of water held constant at 2 inches.

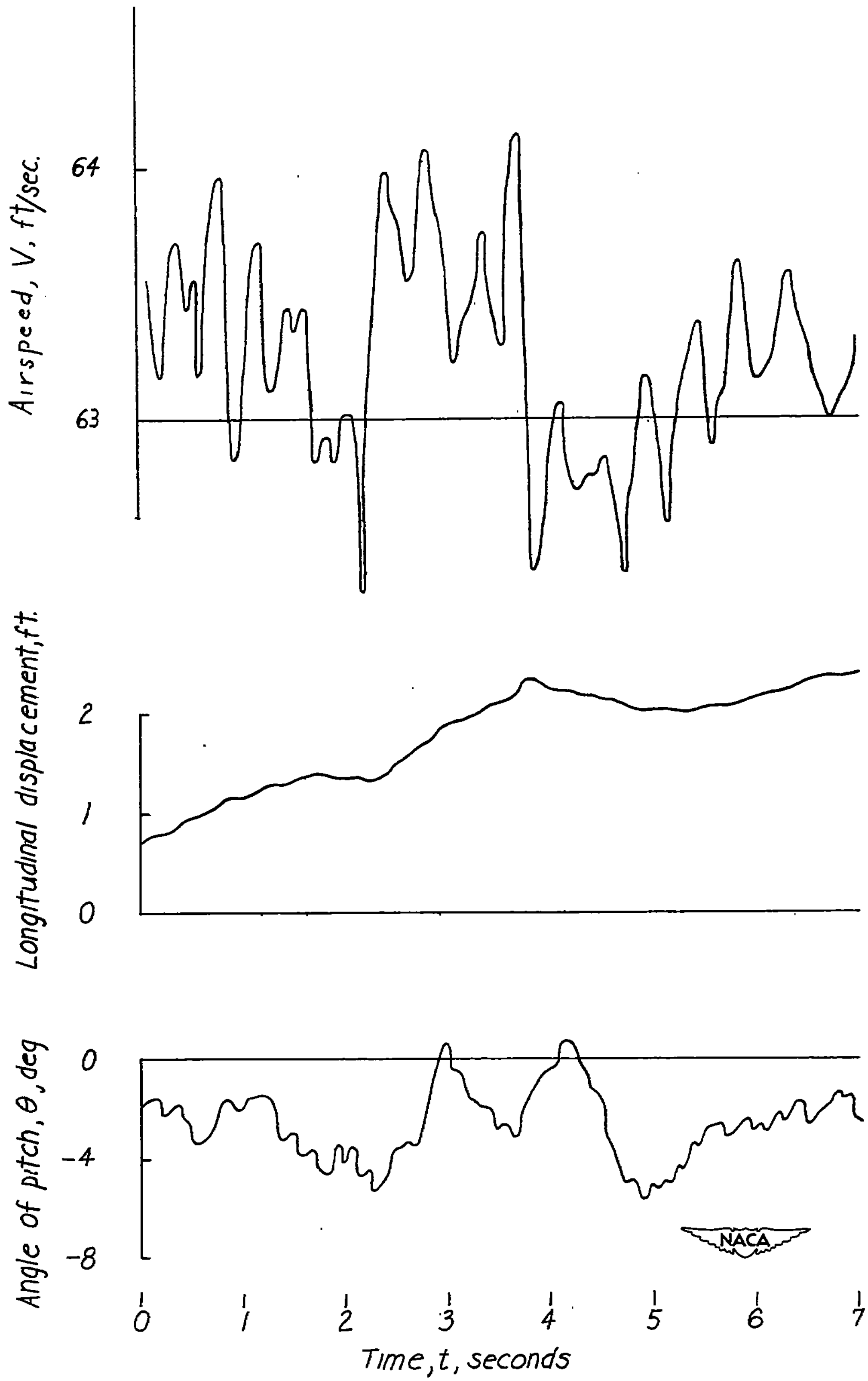


Figure 15.- Time histories of the longitudinal motions of the model for mass condition A_3.